Pulse Sequence Design for EPI and Non-Cartesian Sampling

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1 Introduction

There are a number of ways to speed up MRI, and departing from a conventional spin-warp or raster scan of k-space is one widely used method. This lecture will discuss pulse sequence design for some commonly-used k-space trajectories, including echo-planar imaging (EPI), radial (or projection reconstruction) k-space scanning, and spiral k-space scanning [1, 2]. It will explore the implications of the choice of k-space trajectory on the implementation and properties of the resulting pulse sequence.

There are many different variants of EPI, radial and spiral scans, so that general statements about the imaging properties of EPI, for example, will not always be applicable to every EPI variant. Still, there are some general principles of pulse sequence design, and it is important when designing a pulse sequence to understand the design tradeoffs and to know the comparative strengths of competing techniques. The organization of this syllabus is to first introduce EPI, radial and spiral k-space scans and then discuss some pulse sequence design principles and how these principles apply to these methods.

2 EPI, Radial and Spiral Scans

Figure 1 shows a single-shot EPI k-space trajectory and the corresponding readout gradients and ADC window for this trajectory [1–3]. The sequence begins by moving out to a corner of k-space before starting data acquisition and then collects a series of parallel lines in k-space, moving back and forth along the k_x axis. The motion along the k_y axis is achieved through a series of gradient blips, so this is called a blipped EPI trajectory. An alternative to using blips is to use a constant G_y gradient, which requires less gradient power, but leads to variable k-space sampling density and complicates image reconstruction. Other variations of EPI include those with sinusoidal G_x gradients, interleaved multi-shot versions [4], and versions that collect a circular region instead of a rectangular region [5].

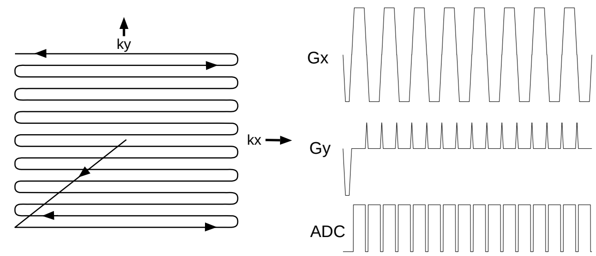

Figure 1: EPI k-space trajectory (left) and corresponding readout gradients and ADC window (right).

Figure 2 shows a radial k-space trajectory and the corresponding readout gradients and ADC window for one of the radial spokes [2,6]. The sequence begins by moving to the edge of a disk in k-space before starting data acquisition, then collects data while scanning across to the other edge of the disk along a line passing through the origin of k-space. The gradients are then rotated on subsequent acquisitions to acquire lines at different angles

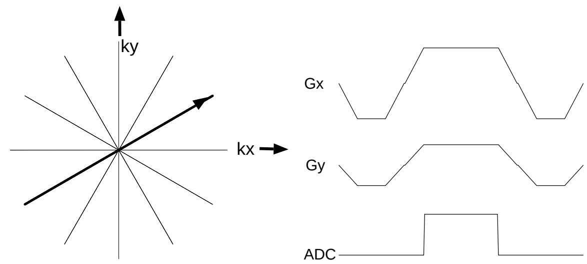

Figure 2: Radial k-space trajectory (left) and corresponding readout gradients and ADC window for one of the radial spokes (right).

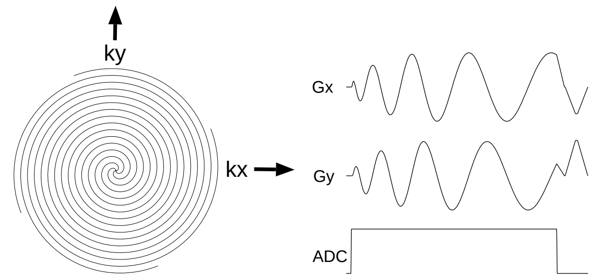

Figure 3: Interleaved spiral k-space trajectory (left) and corresponding readout gradients and ADC window for one of the interleaves (right).

through the origin until all of k-space is filled in. This sequence is also referred to as projection reconstruction (PR) imaging, because the 1D Fourier transforms of the received signals correspond to projections through the object at different angles as in computed tomography (CT). Thus, the image can be reconstructed using CT algorithms such as filtered backprojection, although k-space techniques such as gridding [7] also work well. The sequence shown is a two-sided radial sequence, meaning that each acquisition acquires data on both sides of the origin. Single-sided versions are also possible, which require sampling as the gradient ramps up and require twice the number of readouts, but can be used with very short echo times.

Figure 3 shows an interleaved spiral k-space trajectory and the corresponding readout gradients [2, 8, 9]. The sequence traces out an Archimedean spiral starting at the origin and collects data from the beginning of the scan. The G_x and G_y gradients resemble sinusoids in quadrature of gradually decreasing frequency. The gradients are optimized to reach the maximum k-space radius in a given amount of time under gradient risetime and amplitude constraints. After data acquisition ends, the trajectory is rewound to the origin to produce a predictable residual magnetization. The gradients are then rotated on subsequent acquisitions to fill in k-space. The sequence shown is a spiral-out sequence with constant spacing between the spirals, but other versions include spiral-in, spiral-in/spiral-out and variable density sequences. The image reconstruction is typically performed by gridding [2, 7, 9].

3 Design Principles

It is useful to consider some general principles when desiging a pulse sequence for a particular application. An understanding of these principles leads to an understanding of the design tradeoffs involved in choosing and optimizing a particular sequence. The following sections discuss some design principles and how they apply to to EPI, radial and spiral scanning.

3.1 Scan Time

Reduced scan time is often the primary reason for using EPI or non-Cartesian scanning. General factors that reduce scan time are (1) higher data acquisition (ADC) duty cycle, (2) covering less k-space, and (3) higher average k-space velocity.

Higher ADC duty cycle results from minimizing the time spent applying RF pulses and the associated slice-select and refocusing gradients, as well as minimizing the time spent on dephasing, refocusing, and rewinder gradients associated with the readout itself. It is straightforward to look at a proposed pulse sequence and see what fraction of the time the ADC is on, and this is an important consideration for not only minimizing scan time, but also for maximizing signal-to-noise (SNR) efficiency. Single-shot EPI has a high ADC duty cycle, because only one excitation pulse is used. There is some time lost in the dephasing gradient used to move to the corner of k-space, as well as some time typically lost during the blips. Interleaved EPI has a lower duty cycle, because of additional RF pulses needed, but still many fewer RF pulses than are need for a conventional 2DFT acquisition. Interleaved spiral scans are also very efficient, in that the ADC is on from the beginning of the readout until the beginning of the optional rewinder gradient. Radial acquisitions have relatively low ADC duty cycles, because they require more readouts than conventional 2DFT scans to fully sample k-space.

There are a number of ways to cover less k-space to reduce scan time, One way is to collect a circular region of k-space, rather than a square region. This results in a $\pi/4$ decrease in area covered and an isotropic impulse response. A non-apodized version of the square k-space does contain additional information and thus produces higher spatial resolution along the x-y diagonal directions, but usually an isotropic response is preferred. Spiral and radial acquisitions naturally collect circular regions of k-space, and circular EPI is also possible, although not yet common [5]. Another way to collect less k-space data is by using partial k-space reconstruction to fill in missing k-space. This is commonly done in EPI scans, and is possible with radial and spiral imaging, although less common. Simply undersampling the higher spatial frequencies and allowing the energy there to alias is a technique often used in radial scanning, and the resulting aliasing is often tolerable, particularly for angiographic studies [10]. Variable-density spiral scans are also often undersampled at the edge of k-space [11]. Other methods of reducing the required k-space data include collecting a rectangular FOV in EPI, restricting the FOV along one direction using the temporal anti-aliasing filter in EPI, and parallel imaging. Parallel imaging reconstruction involves more computation for radial and spiral scanning than for conventional 2DFT scans, but may have advantages in reduced noise amplification [12].

The last general method for reducing scan time is to scan with higher average k-space velocity, which corresponds to using a higher average readout gradient magnitude, $\sqrt{G_x(t)^2 + G_y(t)^2}$. In a one-dimensional scan, this would only be limited by the available gradient strength and sampling bandwidth. However, in a 2D scan, turning in k-space becomes necessary, and this requires gradient switching. This switching requires more voltage from the gradient amplifiers and ultimately is limited by peripheral nervous stimulation. Thus, fewer turns and more gentle turning typically allows a higher average k-space velocity. Radial acquisitions have the highest average k-space velocity during the readout, because they are essentially a series of 1D scans. (However, as mentioned above, they have the lowest ADC duty cycle.) Spiral scans have fairly high average k-space velocity, because the gradient amplitude is gradually shifted from one readout axis to the other. Spiral scans are at lower velocity at the beginning of the scan because of risetime limitations and then are at constant velocity for the rest of the scan. EPI scans have varying velocity throughout the scan, as the readout gradient oscillates.

3.2 SNR Efficiency

SNR efficiency is related to flip angle, repetition time (TR), ADC time, and the k-space sampling pattern, among other factors. If a long TR is required by the application (e.g., because of cardiac gating), then EPI or spiral scans with high flip angles and long ADC times have higher SNR efficiency than segmented 2DFT or radial scans with much shorter readouts. On the other hand, for ungated balanced SSFP scans, the flip angle is typically similar for various trajectories, so ADC duty cycle (discussed above) should be high for high SNR efficiency.

If no *a priori* object k-space distribution is assumed, then the optimal SNR is achieved with uniform k-space sampling. To achieve uniform k-space sampling, the k-space trajectory should be uniform and the k-space velocity along the trajectory should be constant. Both EPI and constant-density spiral trajectories are nearly uniform, whereas radial trajectories have significant oversampling at the center of k-space. Thus, radial and variable-density spiral trajectories lose some SNR efficiency, although oversampling the center of k-space has advantages in reducing motion artifacts, as discussed below. The k-space velocity of the different scans was discussed above.

3.3 Motion Sensitivity

It is often important for a pulse sequence to be relatively insensitive to motion, such as that arising from respiration, cardiac motion, or flowing blood. When designing a k-space trajectory, motion sensitivity can be reduced by (1) acquiring the center of k-space when the net in-plane gradient moments are small, (2) avoiding discontinuities in the phase or magnitude of the k-space data to avoid ghosting, (3) encoding x and y information at the same time to avoid oblique flow artifacts, and (4) repetitively acquiring the center of k-space to average out the effects of motion.

Spiral scanning has all of these properties and tends to be relatively resistant to flow and motion artifacts, although artifacts and blurring can still occur [9, 13]. Spiral-out scans have zero in-plane moments at the center of k-space, and the moments during the scan are arranged so that the main effect is blurring along the direction of motion, with good resolution perpendicular to the direction of motion and no discontinuities in k-space. Single-sided radial acquisitions also have meet all of these requirements, with their short readouts further improving their motion robustness [14]. Two-sided radial acquisitions require somewhat more care to meet the requirements, but symmetrical balanced-SSFP versions also have very good motion robustness. Motion sensitivity is a weakness of classic EPI, in that each of the above criteria are violated. However, interleaved EPI has been adapted to produce very good images of the heart, by reducing the echo time through partial k-space acquisition along k_y and other techniques such as flyback acquisitions [15].

3.4 Image Artifacts

Common image artifacts in EPI and non-Cartesian sampling include ghosting, geometric distortion, and image blurring [1, 2]. Some of the sources of these artifacts include B0 inhomogeneity, chemical shift, eddy currents, timing delays, filter anisotropy, T2 decay and motion. Because of the back and forth nature of the EPI scan, many of these sources cause image ghosting in EPI, because there is a periodic modulation in k-space. Typically, phase reference scans are performed and used during image reconstruction of EPI scans to reduce or eliminate image ghosting. EPI scans also tend to suffer from geometric distortion in the presence of B0 inhomogeneity, so it is important to use a good shim or to correct for these distortions. Radial scans are usually less sensitive to image artifacts, because they are composed of many short readouts and because of symmetry. However, radial scans are sensitive to timing errors and have some image blurring in the presence of inhomogeneity. Spiral scans are relatively insensitive to eddy currents, but they do require accurate calibration for gradient delays. The principal limitation of spiral scans is image blurring from B0 inhomogeneity, so some correction for this blurring during image reconstruction is required for spiral scans.

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